# UNITED STATES PATENT APPLICATION FOR:

# ELECTRICAL BIAS DURING WAFER EXIT FROM ELECTROLYTE BATH

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# ELECTRICAL BIAS DURING WAFER EXIT FROM ELECTROLYTE BATH

## CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims benefit of United States provisional patent application serial number 60/463,861, filed April 18, 2003, which is herein incorporated by reference.

## BACKGROUND OF THE INVENTION

### Field of the Invention

[0002] Embodiments of the invention generally relate to a method for withdrawing or removing a semiconductor substrate from a processing fluid.

### Description of the Related Art

[0003] Metallization of sub-quarter micron sized features is a foundational technology for present and future generations of integrated circuit manufacturing processes. More particularly, in devices such as ultra large scale integration-type devices, *i.e.*, devices having integrated circuits with more than a million logic gates, the multilevel interconnects that lie at the heart of these devices are generally formed by filling high aspect ratio, *i.e.*, greater than about 4:1, interconnect features with a conductive material, such as copper. Conventionally, deposition techniques such as chemical vapor deposition (CVD) and physical vapor deposition (PVD) have been used to fill these interconnect features. However, as the interconnect sizes decrease and aspect ratios increase, void-free interconnect feature fill via conventional metallization techniques becomes increasingly difficult. Therefore, plating techniques, *i.e.*, electrochemical plating (ECP) and electroless plating, have emerged as promising processes for void free filling of sub-quarter micron sized high aspect ratio interconnect features in integrated circuit manufacturing processes.

[0004] In an ECP process, for example, sub-quarter micron sized high aspect ratio features formed into the surface of a substrate (or a layer deposited thereon) may be efficiently filled with a conductive material. ECP plating

processes are generally two stage processes, wherein a seed layer is first formed over the surface features of the substrate (generally through PVD, CVD, or other deposition process in a separate tool), and then the surface features of the substrate are exposed to an electrolyte solution (in the ECP tool), while an electrical bias is applied between the seed layer and a copper anode positioned within the electrolyte solution. The electrolyte solution generally contains a source of metal that is be plated onto the surface of the substrate, and therefore, the application of the electrical bias causes the metal source to be plated onto the biased seed layer, thus depositing a layer of the ions on the substrate surface that may fill the features.

**[0005]** However, the decreasing size of features being filled by ECP processes in semiconductor processing requires that the plating process generate minimal defects in order to produce viable devices. Research has shown that a primary cause of plating defects is the presence of air bubbles on the surface of the substrate being plated. Generally, air bubbles are formed on the surface of the substrate during the process of immersing the substrate into the plating solution. More particularly, as the substrate is transitioned from the air into the plating solution, small bubbles of air often adhere to the surface of the substrate. These air bubbles prevent the electrolyte solution from contacting the substrate surface at that particular location, and therefore, prevent plating at that location, which in turn forms a defect in the plated layer. Bubbles adhering to the substrate surface during immersion may also dislodge and travel across the surface of the substrate once its immersed in the plating solution, which may generate multiple defects in multiple locations along the bubble path. Therefore, it is desirable to immerse substrates into electrolyte solutions using an immersion method that is configured to minimize bubble formation. The immersion process also generally includes applying a forward or plating bias to the substrate during the immersion process. This bias is generally applied to counteract etching of the seed layer on the substrate by the plating solution, which is generally an acidic solution, as will be discussed herein.

[0006] Further, once a substrate has been processed in an electrochemical plating cell, the substrate is generally removed from the cell for processing in other cells, such as bevel clean or spin rinse dry cells, for example. However, there is an inherent delay in time between the time when substrate processing is completed and the time when the substrate is removed from the plating solution, which is generally a low pH solution. During this time period, which may be as little as 0.1 seconds or as much as several seconds, the plating solution is able to react with and possibly etch the layer that was just plated onto the substrate in the plating cell. This reaction or etching of the plated layer has been shown to detrimentally affect the surface characteristics of the plated layer. More particularly, post processing etching of the plated layer by the acidic solution has been shown to affect the surface roughness and reflectivity of the plated layer. This is important to plating processes, as the surface roughness and reflectivity of a plated layer may have a substantial impact on the effectiveness of subsequent processes, such as defect detection and polishing processes.

[0007] Another challenge presented by conventional withdrawal schemes is additive consumption. It is generally known in the art that plating solution additives adsorb to the plated surface. As such, when the substrate is removed from the plating solution after a plating process has been completed, those additives that have adsorbed onto the surface are inherently removed also. Thus, withdrawal of the substrate substantially contributes to additive consumption.

[0008] Therefore, there is a need for a method for removing or withdrawing a substrate from an electrochemical plating solution, wherein the method is configured to prevent etching of the plated layer by the plating solution, and further, to minimize additive consumption.

## SUMMARY OF THE INVENTION

[0009] Embodiments of the invention generally provide a method for immersing a substrate into a plating solution with minimal bubble formation and a method for withdrawing the substrate from the plating solution. The immersion

method generally includes biasing the substrate during the immersion process to prevent the plating solution from etching the substrate surface, and in particular, the thin seed layer formed thereon, prior to beginning the plating process. The immersion method further includes tilting and/or rotating the substrate during the immersion process to minimize bubble formation and adherence to the substrate surface during the immersion process. Once the substrate is immersed and a plating process is completed, the method of the invention includes withdrawing the substrate from the solution while applying a removal bias to the substrate. The removal bias is a forward or plating bias configured to prevent the plating solution from etching the surface of the layer that was just plated onto the substrate. As such, the removal bias is configured to prevent the plating solution from etching the surface of the plated layer and generating a roughened or less reflective surface that may be detrimental to post plating processes.

[0010] Embodiments of the invention may further provide a method for removing a substrate from a processing fluid contained in a processing cell. The method includes tilting the substrate to a tilt angle, rotating the substrate, vertically moving the substrate upward out of the processing fluid, and applying an electrical removal bias to the substrate during the vertical movement of the substrate out of the processing fluid.

[0011] Embodiments of the invention may further provide a method for removing a substrate from a plating cell. The method includes vertically actuating the substrate to remove the substrate from a plating solution contained in the plating cell, applying an electrical removal bias to the substrate during the vertical actuation of the substrate, and controlling the electrical removal bias to maintain a constant current density across a plating surface of the substrate during the vertical actuation.

## BRIEF DESCRIPTION OF THE DRAWINGS

[0012] So that the manner in which the above recited features of the present invention can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to embodiments,

some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only typical embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

[0013] Figure 1 is a top plan view of one embodiment of an electrochemical plating system of the invention.

[0014] Figure 2 illustrates a partial perspective and sectional view of an exemplary plating cell used in the plating system of the invention.

[0015] Figure 3 illustrates a sectional view of a plating cell and head assembly during a substrate transfer process.

[0016] Figure 4 illustrates a sectional view of a plating cell and head assembly during a tilting process.

[0017] Figure 5 illustrates a sectional view of a plating cell and head assembly during an immersion process, *i.e.*, during vertical actuation.

[0018] Figure 6 illustrates a sectional view of a plating cell and head assembly during a tilting process after immersion.

[0019] Figure 7 illustrates a sectional view of a plating cell and head assembly during an immersion process wherein the head assembly is positioning the substrate deeper in the plating solution.

[0020] Figure 8 illustrates a sectional view of a plating cell and head assembly positioned in a processing position.

[0021] Figure 9 illustrates a view of the substrate area during immersion.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0022] Embodiments of the invention generally provide methods for immersing and removing a substrate from an electrochemical plating solution. The immersion method of the invention is configured to minimize plating defects

by minimizing bubble formation and adhesion to the substrate surface during the immersion process. The immersion method is further configured to minimize etching of a seed layer formed on the surface of the substrate via application of a loading bias to the substrate during the immersion process. The withdrawal method of the invention is configured to prevent etching of the surface of the plated layer via application of a removal bias to the substrate during the time period between the termination of the plating process and the time when the substrate is removed from the plating cell or plating solution.

**Immersion Mechanics**

[0023] The immersion method of the invention generally includes driving or actuating the substrate into the plating solution using a combination of a tilt and swing immersion processes. More particularly, the substrate may be tilted at an angle with respect to horizontal, and then vertically actuated toward the plating solution, while being rotated, which immerses the substrate and maintains a constant angle between the substrate and the upper surface of the plating solution. The combination of the tilt and rotation causes bubbles to be dislodged from the substrate surface and carried away from the substrate surface as a result of the buoyancy of the bubbles. Further, the tilt angle of the substrate may be adjusted during the immersion process, thus generating a swing or pendulum type motion, which also urges bubbles attached to the substrate surface to be dislodged therefrom.

[0024] Figure 1 illustrates a top plan view of an ECP system 100 of the invention. ECP system 100 includes a factory interface (FI) 130, which is also generally termed a substrate loading station. Factory interface 130 includes a plurality of substrate loading stations configured to interface with substrate containing cassettes 134. A robot 132 is positioned in factory interface 130 and is configured to access substrates contained in the cassettes 134. Further, robot 132 also extends into a link tunnel 115 that connects factory interface 130 to processing mainframe or platform 113. The position of robot 132 allows the robot to access substrate cassettes 134 to retrieve substrates therefrom and

then deliver the substrates to one of the processing cells 114, 116 positioned on the mainframe 113, or alternatively, to the annealing station 135. Similarly, robot 132 may be used to retrieve substrates from the processing cells 114, 116 or the annealing chamber 135 after a substrate processing sequence is complete. In this situation robot 132 may deliver the substrate back to one of the cassettes 134 for removal from system 100.

[0025] The anneal chamber 135 generally includes a two position annealing chamber, wherein a cooling plate/position 136 and a heating plate/position 137 are positioned adjacently with a substrate transfer robot 140 positioned proximate thereto, *e.g.*, between the two stations. The robot 140 is generally configured to move substrates between the respective heating 137 and cooling plates 136. Further, although the anneal chamber 135 is illustrated as being positioned such that it is accessed from the link tunnel 115, embodiments of the invention are not limited to any particular configuration or placement. As such, the anneal chamber may be positioned in communication with the mainframe 113.

[0026] As mentioned above, ECP system 100 also includes a processing mainframe 113 having a substrate transfer robot 120 centrally positioned thereon. Robot 120 generally includes one or more arms/blades 122, 124 configured to support and transfer substrates thereon. Additionally, the robot 120 and the accompanying blades 122, 124 are generally configured to extend, rotate, and vertically move so that the robot 120 may insert and remove substrates to and from a plurality of processing cells 102, 104, 106, 108, 110, 112, 114, 116 positioned on the mainframe 113. Similarly, factory interface robot 132 also includes the ability to rotate, extend, and vertically move its substrate support blade, while also allowing for linear travel along the robot track that extends from the factory interface 130 to the mainframe 113. Generally, process cells 102, 104, 106, 108, 110, 112, 114, 116 may be any number of processing cells utilized in an electrochemical plating platform. More particularly, the process cells may be configured as electrochemical plating cells, rinsing cells,

bevel clean cells, spin rinse dry cells, substrate surface cleaning cells, electroless plating cells, metrology inspection stations, and/or other processing cells that may be beneficially used in conjunction with a plating platform. Each of the respective processing cells and robots are generally in communication with a process controller 111, which may be a microprocessor-based control system configured to receive inputs from both a user and/or various sensors positioned on the system 100 and appropriately control the operation of system 100 in accordance with the inputs.

[0027] In the exemplary plating system illustrated in Figure 1, the processing cells may be configured as follows. Processing cells 114 and 116 may be configured as an interface between the wet processing stations on the mainframe 113 and the dry processing regions in the link tunnel 115, annealing chamber 135, and the factory interface 130. The processing cells located at the interface locations may be spin rinse dry cells and/or substrate cleaning cells. More particularly, each of cells 114 and 116 may include both a spin rinse dry cell and a substrate cleaning cell in a stacked configuration. Cells 102, 104, 110, and 112 may be configured as plating cells, either electrochemical plating cells or electroless plating cells, for example. Cells 106, 108 may be configured as substrate bevel cleaning cells. Additional configurations and implementations of an electrochemical processing system are illustrated in commonly assigned United States Patent Application Serial No. 10/435,121 filed on December 19, 2002 entitled "Multi-Chemistry Electrochemical Processing System", which is incorporated herein by reference in its entirety.

[0028] Figure 2 illustrates a partial perspective and sectional view of an exemplary plating cell 200 that may be implemented in processing cells 102, 104, 110, and 112. The electrochemical plating cell 200 generally includes an outer basin 201 and an inner basin 202 positioned within outer basin 201. Inner basin 202 is generally configured to contain a plating solution that is used to plate a metal, *e.g.*, copper, onto a substrate during an electrochemical plating process. During the plating process, the plating solution is generally

continuously supplied to inner basin 202, and therefore, the plating solution continually overflows the uppermost point (generally termed a "weir") of inner basin 202 and is collected by outer basin 201 and drained therefrom for chemical management and/or recirculation. Plating cell 200 is generally positioned at a tilt angle, *i.e.*, the frame portion 203 of plating cell 200 is generally elevated on one side such that the components of plating cell 200 are tilted between about 3° and about 30°, or generally between about 4° and about 10° for optimal results. The frame member 203 of plating cell 200 supports an annular base member 204 on an upper portion thereof. Since frame member 203 is elevated on one side, the upper surface of base member 204 is generally tilted from the horizontal at an angle that corresponds to the angle of frame member 203 relative to a horizontal position. Base member 204 includes an annular or disk shaped recess formed into a central portion thereof, the annular recess being configured to receive a generally disk shaped anode member 205. Base member 204 further includes a plurality of fluid inlets/drains 209 extending from a lower surface thereof. Each of the fluid inlets/drains 209 are generally configured to individually supply or drain a fluid to or from either the anode compartment or the cathode compartment of plating cell 200, wherein the anode compartment generally includes the volume in the cell below the membrane 208 and the cathode compartment includes the volume in the cell above the membrane. Anode member 205 generally includes a plurality of slots 207 formed therethrough, wherein the slots 207 are generally positioned in parallel orientation with each other across the surface of the anode 205. The parallel orientation allows for dense fluids generated at the anode surface during plating to flow downwardly across the anode surface and into one of the slots 207. Plating cell 200 further includes a membrane support assembly 206. Membrane support assembly 206 is generally secured at an outer periphery thereof to base member 204, and includes an interior region configured to allow fluids to pass therethrough. A membrane 208 is stretched across a lower surface of the support 206 and operates to fluidly separate a catholyte chamber and anolyte chamber portions of the plating cell. The membrane support assembly 206 may include an o-ring type seal positioned near a

perimeter of the membrane 208, wherein the seal is configured to prevent fluids from traveling from one side of the membrane 208 secured on the membrane support 206 to the other side of the membrane 208. A diffusion plate 210, which is generally a porous ceramic disk member, is configured to generate a substantially laminar flow or even flow of fluid in the direction of the substrate being plated, and (not shown) is positioned in the cell between membrane 208 and the substrate being plated. The exemplary plating cell is further illustrated in commonly assigned United States Patent Application Serial No. 10/268,284, which was filed on October 9, 2002 under the title "Electrochemical Processing Cell", claiming priority to United States Provisional Application Serial No. 60/398,345, which was filed on July 24, 2002, both of which are incorporated herein by reference in their entireties.

**[0029]** As noted above, in order to minimize defects in plated films, bubbles adhering to the substrate surface during the process of immersing the substrate into the plating solution contained in a plating cell should be minimized. Therefore, embodiments of the invention provide a method for immersing a substrate into a processing fluid that generates minimal bubbles. The immersion method of the invention begins with the process of loading a substrate into a head assembly 300, as illustrated in Figure 3. The head assembly 300 generally includes a contact ring 302 and a thrust plate assembly 304 that are separated by a loading space 306. A more detailed description of the contact ring 302 and thrust plate assembly 304 may be found in commonly assigned U.S. Patent Application Serial No. 10/278,527, which was filed on October 22, 2002 under the title "Plating Uniformity Control By Contact Ring Shaping", which is hereby incorporated by reference in its entirety. A robot, such as robot 120 illustrated in Figure 1, is used to position a substrate on the contact ring 302 via access space 306. More particularly, robot 120 may be a vacuum-type robot configured to engage a backside of the substrate with a reduced pressure engaging device. The substrate may then be supported in a face down (production surface facing down) orientation with the vacuum engaging device attached to the backside or non-production surface of the substrate. The robot may then extend into contact

ring 302 via access space 306, lower to position the substrate on the contact pins/substrate support surface of contact ring 302, disengage the vacuum engaging device, raise to a withdrawal height, and then withdraw from the contact ring 302 leaving the substrate positioned thereon.

[0030] Once the substrate is positioned on the contact ring 302, thrust plate assembly 304 may be lowered into a processing position. More particularly, Figure 3 illustrates thrust plate 304 in a substrate loading position, *i.e.*, thrust plate 304 is vertically positioned above the lower surface of contact ring 302 such that the access space 306 is maximized. In this position, robot 120 has the most amount of space available to loading the substrate onto the contact ring 302. However, once the substrate is loaded, thrust plate 304 may be actuated vertically, *i.e.*, in the direction indicated by arrow 410 in Figure 4, to engage the backside of the substrate positioned on the contact ring 302. The engagement of the thrust plate 304 with the backside of the substrate positioned on the contact ring 302 operates to mechanically bias the substrate against the electrical contact pins positioned on contact ring 302, while also securing the substrate to the contact ring 302 for processing.

[0031] Once the substrate is secured to the contact ring 302 by the thrust plate 304, the lower portion of the head assembly 300, *i.e.*, the combination of the contact ring 302 and the thrust plate 304, are pivoted to a tilt angle. The lower portion of the head assembly is pivoted to the tilt angle via pivotal actuation of the head assembly about a pivot point 408. The lower portion of head assembly 300 is actuated about pivot point 408, which causes pivotal movement of the lower portion of head assembly 300 in the direction indicated by arrow 409 in Figure 4. The lower portion of head assembly 300 and the plating surface of the substrate positioned on the contact ring 302 are tilted to the tilt angle as a result of the movement of head assembly 300, wherein the tilt angle is defined as the angle between horizontal and the plating surface/production surface of the substrate secured to the contact ring 302. The tilt angle is generally between about 3° and about 30°, and more particularly, between about 3° and about 10°.

[0032] Once the head assembly 300 is tilted, it may be actuated in the Z-direction to begin the immersion process. More particularly, head assembly 300 may be actuated in the direction indicated by arrow 501, as illustrated in Figure 5, to bring the substrate positioned in the contact ring 302 toward the plating solution contained within the plating cell 504 positioned below head assembly 300. Plating cell 504, which is generally similar to plating cell 200 illustrated in Figure 2, is configured to contain a plating solution therein. The plating solution is generally contained within the inner weir of the plating cell 504 and overflows the uppermost point 502 of the inner weir. Therefore, as head assembly 300 is moved toward plating cell 504, the lower side of contact ring 302, *i.e.*, the side of contact ring 302 positioned closest plating cell 504 as a result of the tilt angle, contacts the plating solution as the head assembly 300 is actuated toward cell 502. The process of actuating head assembly 300 toward cell 502 may further include imparting rotational movement to contact ring 302. Thus, during the initial stages of the immersion process, contact ring 302 is being actuated in a vertical or Z-direction, while also being rotated about a vertical axis extending upward through head assembly 300. Generally, the vertical axis about which contact ring 302 is rotated is generally orthogonal to the substrate surface. The process of immersing the substrate into the plating solution while applying a bias to the substrate is described in commonly assigned U.S. Patent Application Serial No. 09/766,060, filed on January 18, 2001 entitled "Reverse Voltage Bias for Use in Electro-Chemical Plating System," which claims benefit of United States Patent No. 6,258,220, filed April 8, 1999, both of which are hereby incorporated by reference in their entirety.

[0033] As the substrate becomes immersed in the plating solution contained within plating cell 504, the Z-motion of head assembly 300 is terminated and the tilt position of contact ring 302 is returned to a substantially horizontal position, as illustrated in Figure 6. The termination of the vertical or the Z-direction movement is calculated to maintain the substrate in the plating solution contained in cell 504 when the tilt angle is removed. Further, embodiments of the invention contemplate that the removal of the tilt angle, *i.e.*, the return of

contact ring 302 to a horizontal position, may be conducted simultaneously with the vertical movement of contact ring 302 into the plating solution. As such, embodiments of the invention contemplate that the substrate may first contact the plating solution with the substrate being positioned at a tilt angle, and then the tilt angle may be returned to horizontal while the substrate continues to be immersed into the plating solution. This process generates a unique movement that includes both vertical actuation and tilt angle actuation, which has been shown to reduce bubble formation and adherence to the substrate surface during the immersion process. Further, the vertical and pivotal actuation of the substrate during immersion process may also include rotational movement of contact ring 302, which has been shown to further minimize bubble formation and adherence to the substrate surface during the immersion process.

[0034] Once the substrate is completely immersed into the plating solution contained within cell 504, head assembly 300 may be further actuated in a vertical direction (downward) to further immerse the substrate into the plating solution, *i.e.*, to position the substrate farther or deeper into the plating solution, as illustrated in Figure 7. This process may also include rotating the substrate, which operates to dislodge any bubbles formed during the immersion process from the substrate surface. Once the substrate is positioned deeper within the plating solution, the head assembly 300 may again be pivoted about pivot point 408, so the substrate surface may be positioned at the tilt angle, as illustrated in Figure 8. Further, inasmuch head assembly 300 just actuated the substrate downward into the plating solution in the previous step, the tilting motion illustrated in Figure 8 generally will not raise the surface of the substrate out of the plating solution on the high side of the tilted contact ring. More particularly, since pivot point 408 is positioned in the middle of head assembly 300, when the head assembly pivots the contact ring 302 about pivot point 408, one side of the contact ring 302 is immersed further into the plating solution, while the opposing side of the contact ring 302 is raised upward toward the surface of the plating solution as a result of the pivotal motion. Thus, since the substrate is intended to be maintained within the plating solution once immersed therein, head assembly

300 must be actuated further into the plating solution in order to move the contact ring 302 from the horizontal position illustrated in Figure 7 to the tilted position illustrated in Figure 8 without raising at least a portion of the substrate out of the plating solution. This final tilting motion of head assembly 300 generally corresponds to positioning contact ring 302 in a processing position, *i.e.*, a position where the substrate supported by contact ring 302 is generally parallel to an anode positioned in a lower portion of the plating cell 502. Further, positioning contact ring 302 in the processing position may include further actuating head assembly 300 toward the anode positioned in the lower portion of the plating cell, so that the plating surface of the substrate may be positioned at a particular distance from the anode for the plating process.

**[0035]** Additionally, the immersion process of the invention may include an oscillation motion, *i.e.*, tilting in opposing or different directions, to further enhance the bubble removal process. More particularly, head assembly 300 may be tilted back and forth between a first tilt angle and a second tilt angle in an oscillatory manner, *i.e.*, in a manner where the substrate is tilted between a first angle and a second angle several times, once the substrate is immersed in the plating solution. This tilting motion may be conducted in a quick manner, *i.e.*, from about 2 tilts per second up to about 20 tilts per second. The tilting motion may be accompanied by rotation, which further facilitates dislodging bubbles that are adhering to the substrate surface.

**[0036]** The immersion process of the invention may also include vertical oscillation of the substrate in the plating solution. More particularly, once the substrate is immersed in the plating solution, the substrate may be actuated up and down. When the substrate is raised upward in the plating solution, the volume of solution below the substrate is increased, and therefore, a rapid flow of solution to the area below the substrate is generated. Similarly, when the substrate is lowered, the volume decreases and an outward flow of solution is generated. As such, actuation of the substrate vertically, *i.e.* repeated upward and downward motions, causes reversing or oscillating fluid flows to occur at the

substrate surface. The addition of rotation to the oscillation further increases the oscillating fluid flows across the substrate surface. These oscillating fluid flows have been shown to improve bubble removal, and therefore, decrease defects.

[0037] The immersion process of the invention may further include oscillating the rotation of the substrate once it is immersed in the plating solution. More particularly, the substrate is generally rotated during both the immersion and plating processes. This rotation generally increases fluid flow at the substrate surface via circulation of the depleted plating solution that is generated at the substrate surface. These rotation and fluid flow characteristics may also be used during the immersion process to facilitate bubble removal. More particularly, embodiments of the invention contemplate that the substrate may be rotated at varying rotation rates and in varying directions during and/or after the substrate is immersed. For example, once the substrate is immersed in the solution, the substrate may first be rotated in a clockwise direction for a predetermined period of time before the rotation direction is switched to counter clockwise for a predetermined period of time. The rotation direction may be switched several times, or only once, depending upon the application.

[0038] Additionally, embodiments of the invention may implement a combination of the oscillation methods described above. For example, an immersion process of the invention may include tilt actuation, rotational actuation, and vertical actuation, or any combination thereof.

**Substrate Immersion Bias**

[0039] Figure 9 illustrates a diagram of a substrate surface as the substrate surface is being immersed into electrolyte solution without being rotated and with the substrate tilted from horizontal to a tilt angle. In this embodiment, substrate 907 begins the immersion as the edge of the substrate first contacts the electrolyte solution at a first edge 908 of substrate 907. As the vertical motion of the substrate support member or head assembly continues, the area of the substrate immersed in the electrolyte solution proportionally increases, as illustrated by the shaded area 909. It is to be noted, however, that the shaded

area 909 does not represent the total immersed area. Rather, area 109 generally represents the most recently immersed area, and therefore, the area from the edge of the substrate to the line labeled *j*+1 would represent the total immersed area of the substrate at time *J*+1. Therefore, and in order for a power supply to provide a constant current density across the surface of the substrate during the immersion process, the time varying area of the substrate being immersed may be calculated, or otherwise estimated or determined, and used to determine a time varying current necessary to provide a constant current density across the area of the substrate immersed in the electrolyte solution. As such, embodiments of the present invention supply current to the substrate as a function of the immersion speed of the substrate, as the immersion speed of the substrate, *i.e.*, the vertical rate at which the substrate is immersed into the plating solution, directly corresponds to the change of the immersed area of the substrate during the immersion process. Additionally, although the substrate is generally rotated during the immersion process, the area calculation will be unchanged in non-rotation embodiments, as the rotation of the substrate does not increase or decrease the area of the substrate being immersed in the plating solution per unit time.

**[0040]** The calculation of the time varying area of the substrate immersed in the electrolyte solution generally includes incrementally calculating the area of minute sections of the immersed portion of the substrate and summing the sections together to obtain the total area immersed for a particular time. The calculation and application of current to the substrate during the immersion process is illustrated in co-pending and commonly assigned United States Patent Application Serial No. 10/135,546, entitled Apparatus and Method for Regulating the Electrical Power Applied to a Substrate During Immersion, filed on April 29, 2002, which is hereby incorporated by reference in its entirety. Further, although the referenced application is generally directed to controlling an immersion bias, Applicants contemplate that the methodology may be utilized to control a removal bias, as will be further discussed herein.

[0041] In one embodiment of the invention, the current supplied to the substrate is increased as the immersion surface area increases in accordance with a time calculation. For example, the total time for an immersion process can be determined through experimentation. Thereafter, a correlation between the elapsed time in the immersion process and the immersed surface area can be determined through calculation. As such, with the correlation between the elapsed time and immersion area determined, the current and supply to the substrate can then be determined in accordance with the increase in the immersion time, as the time is proportional to the immersion area. Therefore, knowing the correlation between the immersion time and the immersion surface area, processing recipes can be modified to include a proportional change in the current supplied to the substrate during the immersion process so that a uniform current density across the immersed surface area can be maintained throughout the immersion process.

[0042] In another embodiment of the invention, a sensor may be used to determine the exact radial or tilting position of the substrate during the immersion process. As such, the position is transmitted to the controller, which may then calculate the immersed area in a real-time manner. The calculated, immersed area may then be used to determine the current to be supplied to the substrate in order to maintain a uniform current density across the immersed substrate area. The granularity/incremental section sampling of the measurement process may be increased simply by taking more measurements per unit time, and therefore, adjusting the current supplied to the immersed surface area more per unit time. Although the end result of the present embodiment is to provide a uniform current density across the immersed surface area of the substrate, the present embodiment also provides for a uniform current density across the immersed area of the substrate during nonuniform immersion processes. For example, if the immersion speed of the substrate is not constant or is not repeatable between respective immersion processes, the invention may be utilized to maintain a uniform current density across the immersed area of the substrate regardless of the immersion speed, as the current calculation is independent of

the elapsed immersion time. Therefore, the feedback loop type system of the present embodiment may provide advantages over other embodiments of the invention in specific configurations wherein the elapsed time of the immersion process is not constant across several substrate immersions.

[0043] In order for the immersion bias applied to the substrate to be effective in reducing the erosion or etching of the seed layer by the acidic plating solution, the voltage and current applied between the substrate and anode must be sufficient to generate a plating rate that will equal or overcome the erosion or etching rate of the solution on the seed layer. Generally, the voltage will be in the range of between about 0.7 volts and about 20 volts. Similarly, the current applied to the substrate is generally configured to generate a constant current density across the surface of the substrate of between about 0.5 mA/cm$^2$ and about 3 mA/cm$^2$. The actual current and/or voltage applied to the substrate may be monitored and/or varied in order to maintain a constant current density across the surface of the substrate.

**Substrate Withdrawal Mechanics and Bias**

[0044] Plating processes involve applying an electrical bias to the substrate via the contact ring 302. The plating bias is a forward bias, *i.e.*, the plating bias is configured such that the substrate is electrically charged to be more negative than the anode 205 in the plating cell, so that the positively charged metal ions in the plating solution will plate on the negatively charged substrate. In conventional plating systems, once the plating process is completed, the electrical bias is terminated and the substrate is removed from the plating cell. However, as noted above, conventional plating systems and methods generally include time delay between the termination of the plating bias and the removal of the substrate from the plating solution. During this time delay, the substrate is in contact with the plating solution, and since plating solutions are often acidic in nature, the plating solution can etch the surface of the plated layer during the time delay. This etching causes the smooth surface of the plated layer to

roughen and decrease in reflectivity, which is not beneficial to subsequent processing steps, such as defect inspection and CMP processes.

[0045] Therefore, the method and apparatus of the present invention is configured to apply a forward substrate removal bias (the substrate is negative relative to the anode) to the substrate during the delay time and the removal process. The removal bias is configured to prevent etching of the surface of the plated layer, and therefore, the removal bias is configured to preserve the smooth surface of the plated layer. The removal bias is generally applied to the substrate immediately after the plating bias is terminated, *i.e.*, the transition from the plating bias to the removal bias may be seamless, such that the substrate is not exposed to the plating solution without a forward bias applied thereto. The removal bias is calculated to be sufficient to prevent or counteract etching of the plated layer, however, the removal bias may also configured to minimize deposition on the surface of the plated layer. As such, the removal bias may be configured to be just above the plating potential of the system, and the driving current of the removal bias may be minimized, *i.e.*, just enough current to prevent etching while not causing significant deposition on the smooth upper surface of the plated layer.

[0046] In similar fashion to the immersion bias control features of the invention described above, embodiments of the invention are also configured to control the current applied during the removal or withdrawal bias. For example, controller 111 may be used to control the current and/or voltage applied to the substrate during the withdrawal process. The electrical current or voltage supplied to the substrate during withdrawal may be controlled in order to prevent additional deposition on areas of the substrate that remain immersed in the plating solution longer than other areas of the substrate, as deposition thickness in an electrochemical plating process is generally a function of exposure time to the plating solution. Further, the voltage or current may be controlled during the substrate withdrawal process in order to prevent the current density on the immersed portion of the substrate from increasing, which will also generally

cause an increased plating rate on the portions of the substrate that remain immersed in the plating solution.

[0047] Embodiments of the invention contemplate that either a voltage control (control system where the voltage is monitored and adjusted in order to control the electrical current or power applied) or a current control system (control system where the current itself is monitored and controlled) may be used to control the removal bias. A current control system may be used to control the removal bias by maintaining a constant current density across the substrate surface during the entire substrate removal process. More particularly, as noted above with regard to maintaining a constant current density across the substrate surface during the immersion process, as the substrate is removed from the plating solution, the resistance of the electrical circuit supplying the removal bias changes. The resistance change is a result of the decreasing immersed conductive surface area of the substrate, which results in an increase in the resistance of the circuit. Therefore, as the resistance of the circuit increases and the immersed surface area decreases, the current control system of the invention may react to these changes to decrease the current supplied to the substrate so that the current density across the surface of the substrate remains constant through the withdrawal process.

[0048] The control system may control the current in a closed loop manner, *i.e.*, the current control system may be configured to measure the resistance or other electrical parameter of the removal bias circuit and control the current supplied thereto accordingly. Alternatively, the current control system may be configured to control the removal bias in response to a mechanical condition, such as the position of the substrate or another measurable mechanical parameter. For example, the position of the substrate, *i.e.*, the vertical position of the substrate relative to the plating solution during the withdrawal process, may be correlated with the immersed surface area of the substrate, and therefore, the position of the substrate may also be used to control the electrical removal bias applied to the substrate. Further still, the electrical bias may be controlled in a

time dependent manner, *i.e.*, the electrical removal bias may be adjusted per unit of time that the substrate continues through a removal process, thus essentially equating time or duration of the removal process with the immersed surface area of the substrate.

**[0049]** During the substrate removal process, the substrate may be rotated, tilted, pivoted, vertically actuated, horizontally actuated, and/or vibrated with sonic or ultrasonic energy. For example, during a removal process of the invention, a substrate may be rotated in the plating solution while the removal bias is initiated. The substrate may then be raised vertically out of the solution to remove the substrate from the solution. During the raising process the surface area of the substrate is incrementally removed from the plating solution and the electrical bias supplied thereto is controlled in accordance with the proportion of the surface area removed from the solution (or remaining in the solution), as noted above. The substrate may be held in a horizontal position, *i.e.*, in a position where the surface of the substrate is generally parallel to the upper surface of the plating solution contained in a weir-type plater.

**[0050]** Alternatively, the surface of the substrate may be tilted from horizontal, *i.e.*, the surface of the substrate may be positioned such that a tilt angle is formed between the substrate surface and the upper surface of the plating solution in a weir-type plater. In this configuration, when the substrate is vertically moved or raised out of the solution, the tilt angle between the substrate surface and the upper surface of the plating solution remains constant. However, embodiments of the invention also contemplate that the tilt angle may be varied during the removal process. For example, the tilt angle may be increased or decreased during the substrate removal process, such that the vertical movement of the substrate out of the solution does not result in the tilt angle remaining constant, rather, the tilt angle increases or decreases as the substrate is removed.

**[0051]** During the removal process, for example, the substrate may be rotated between about 5 rpm and about 100 rpm, or more particularly, between about 20

rpm and about 60 rpm. The tilt angle of the substrate may be between about 3° and about 30°, or more particularly, between about 5° and about 20°. The tilt angle may also be increased or decreased, as well as pivoted or oscillated during the removal process. The electrical bias applied to the substrate during the removal process may be configured to generate an electrical current density across the surface of the substrate of between about 0.5 $mA/cm^3$ and about 5 $mA/cm^3$, or more particularly, between about 0.5 $mA/cm^3$ and about 1 $mA/cm^3$, or more particularly, between about 1.0 $mA/cm^3$ and about 3 $mA/cm^3$. The voltage applied to the substrate during removal may be between about 0.3 volts and about 5 or about 10 volts, for example, and more particularly, between about 0.8 volts and about 5 volts.

**[0052]** In another embodiment of the invention, the method for maintaining a uniform current density across the surface of the substrate is utilized during the process of removing a substrate from a plating cell. For example, once a plating process for a substrate is complete, the substrate is removed from the plating chamber by essentially reversing the steps of the immersion process. In the reverse immersion process, it may be desirable to maintain a constant current density across the immersed surface of the substrate in order to avoid variances in uniformity, in similar fashion to the constant current density maintained during the immersion process. Therefore, in the reverse immersion process, the current supplied to the substrate will generally be constant while the entire surface area of the substrate is immersed in the plating solution. However, once the surface of the substrate begins to be removed from the plating solution, the current supplied thereto may be decreased in proportion to the immersed area of the substrate. This essentially operates to maintain a uniform current density across the immersed area of the substrate throughout the process. The process of controlling the current to the substrate during the reverse immersion process is, for example, conducted to a feedback loop type system or a time varying current control type system, as discussed in the previous embodiments. Regardless of the type of current control system implemented, the current supplied to the

substrate during the reverse immersion process will generally be proportional to the surface area of the substrate remaining immersed in the plating solution.

[0053] While the foregoing is directed to embodiments of the present invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.